Final Report for Grant DE-FG02-90ER61072

Summary

Our research group at ASRC was involved from the beginning of the DOE Atmospheric Radiation Measurement Program (ARM) effort; we designed the Multi-filter Rotating Shadowband Spectroradiometer (MFRSR) which was widely deployed (and still operational in ARM) and through the years did a wide variety of data analysis on the returned data from these instruments. We also developed the Rotating Shadowband Spectroradiometer, which ARM deployed and also still deploys. Many scientific papers have been written using the data from these instruments, and the ongoing data streams remain part of the current ARM effort. Earlier reports contain our progress from previous grant periods, this report covers the last period and provides references to published work.

Report

We have operated RSS instruments built by ASRC for ARM since 1997. These have provided the only continuously-available spectra in the 360 - 1100 nm domain taken by the ARM program, and are used for a wide range of derived products. The first commercially-built Rotating Shadowband Spectroradiometer (RSS) is operating now at SGP. This involved a major transfer of technology from us to Yankee Environmental Systems (the commercial manufacturer of the instrument now at SGP). We also did extensive acceptance testing, and significant rework, and are handling the data now. Dr. P. Kiedron is now the RSS instrument mentor. We have also deployed automated irradiance calibrators we have developed to SGP. Recently-published scientific results of our efforts are presented in the papers listed below.

MFRSR and RSS data are used for the aerosol optical depth VAP, the methods for this were developed here and we assisted the implementation of this VAP by ARM. A cloud optical depth VAP using algorithms developed here is nearing operation.

At present, we have reduced measurement uncertainties in *broadband* diffuse-sky shortwave irradiances to ≈ 5 W/m2. The diffuse-shortwave energy-budget discrepancies between measurements and models are now within the range caused by uncertainty of the surface spectral albedo (which varies substantially in the domain near the SGP facility due to crop and land-use practices), and secondarily aerosol optical properties aloft: single scattering albedo and phase-functions.

The effective surface-albedo "seen" by a measurement taken at SGP depends on the vertical distribution of scatterers; under clear-sky conditions the surface albedo "footprint" is large and sensitive to aerosol scattering phase function.

However, our understanding is not as complete as the broadband-energy budget assessment appears to make it. When spectral clear-sky diffuse/direct ratios are examined (these ratios are available from RSS data directly, and not dependent on calibration, because the measurement technique makes them intrinsically ratiometric) significant spectral discrepancies have been seen on the clearest days we have available at SGP. The total energy is approximately 5 W/m2, but the discrepancy is as large as 15% at 360 nm, with a very bland and Angstrom-law behavior.

Some of the remaining errors in our understanding are incongruences between instrument irradiance scales and assumed extraterrestrial spectra. We used Langley derived extrapolations of the exo-atmospheric spectrum, taken from long RSS data series at SGP, to produce an extraterrestrial spectrum which is 4.5% brighter in the mid-visible, qualitatively more similiar to recent measurements by Thuiller et al, and differs from the Wherrli et al. consensus spectrum most used by ARM researchers. Other discrepances with "New-Kurucz" are observable, affecting shorter wavelengths. (Harrison et al. 2003). Thus the broadband-energy budget appears in better shape than it really is; integrating over the entire shortwave spectrum allows compensating errors to mask each other.

It is only under the very clearest sky conditions that these discrepancies become an issue; in more turbid skies the observations can be reproduced by models with adjustments to aerosol parameters well within their measurment uncertainties. Under the clearest conditions we have seen to date the results cannot be explained by models without assuming aerosol single-scattering albedos which are substantially lower than believed present.

Further progress on these issues will require methods to cope with the inhomogeniety (in both time and space) of the spectral surface albedo around the SGP facility, efforts to reduce uncertainty in aerosol optical properties, and tests to ensure that subtle measurement systematic errors are not contributing to the apparent results. Suitable cases are not frequent however, and we are also concerned about subtle instrument/modeling issues.

Cloud Optical Depths have been retrieved using the algorithm described in Min and Harrison [1996] for the SGP scentral facility for the years1997 - 2003.

We have also made significant progress over the last 3 years in O_2 A-band retrievals. We can now retrieve both mean and variance of gamma-fitted pathlength distributions from RSS data, this was the first demonstrated 2-eigenvector retrieval from A-band data so far as we know. The variances are strong discriminators for layered cloud systems, and we believe we can identify cases where mid-level clouds are not sensed by the cloud radar, when lower thick stratus are present.

We participated in the fall 2003 aerosol IOP with 3 RSS instruments, one of them an ultraviolet RSS. Analysis of these data, and operational results from the ARM (Yankee-built) RSS are in progress.

In addition to these efforts, we hosted the Instantaneous Radiative Fluxes (IRF) working group meeting at ASRC, and Lee Harrison was working to organize a Cloud Optical Depth IOP at the SGP site.

Refereed Publications In Print (from the final grant period)

Dutton, E.G., J.J. Michalsky, T. Stoffel, B.W. Forgan, J. Hickey, D.W. Nelson, T.L. Alberta, and I. Reda, *Measurement of broadband diffuse solar irradiance using current commercial instrumentation with a correction for thermal offset errors* , J. Atmos. Oceanic Tech. **18**, No. 3, 297-314, 2001

Joseph, E., and Q.-L. Min, Assessment of multiple scattering and horizontal inhomogeneity in IR radiative transfer calculations of observed thin cirrus clouds, J. Geophys. Res., **108**(D13), 4380, 2003.

Gu, Lianhong, Dennis D. Baldocchi, Steve C. Wofsy, J. William Munger, Joseph J. Michalsky, Shawn P. Urbanski, and Thomas A. Boden, Response of a Deciduous Forrest to the Mount Pinatubo Eruption: Enhanced Photosynthesis, Science **:299,** 2035-2038, 2003.

Harrison, l., P. Kiedron, J. Berndt, and J. Schlemmer, Extraterrestrial solar spectrum 360-1050 nm from Rotating Shadowband Spectroradiometer measurement at the Southern Great Plains site, J. Geophys. Res., **:108**(D14), 4424, 2003.

Kiedron , P., J. Michalsky, B. Schmid, D. Slater, J. Berndt, L. Harrison, P. Racette, E. Westwater and Y. Han, *A Robust Retrieval of Water Vapor Column in Dry Arctic Conditions Using the Rotating Shadowband Spectroradiometer* , , J. Geophys. Res. **106**, 24,007-24,016,2001

Kiedron, P.W. and J.J. Michalsky, Measurement errors in diffuse irradiance with non-Lambertian radiometers, International Journal of Remote Sensing, **:24**, 237-247, 2003.

Kiedron, P., J. Berndt, J. Michalsky, and L. Harrison, Column water vapor from diffuse irradiance, Geophys. Res. Lett., **:30**(11), 1565, 2003.

Kim, B.-G., S. E. Schwartz, M. A. Miller, and Q. Min, Effective radius of cloud droplets by ground-based remote sensing: Relationship to aerosol, J. Geophys. Res., **108**(D23), 4740, 2003.
J. Li, and Q. -L. Min, Parameterization of the Optical Properties of Sulfate Aerosols in the Infrared, *J. Atoms. Sci,* **59***,* 3130-3140, 2002.

Marty, Christoph, Rolf Philipona, Jennifer Delamere, Ellsworth G. Dutton, Joe Michalsky, Knut Stamnes, Rune Storvold, Tom Stoffel, Shepard A. Clough, Eli J. Mlawer, Downward longwave irradiance uncertainty under arctic atmospheres: Measurements and modeling, J. Geophys. Res., **:108**(D12), 4358, 2003.

Michalsky, J.J., Q. Min, P.W. Kiedron, D.W. Slater, and J.C. Barnard, *A Differential Technique to Retrieve Column Water Vapor Using Sun Radiometry* , Journal of Geophysical Research, **106**, D15, 17,433-17,442. 2001

Michalsky , J., J. Schlemmer, W. Berkheiser III, J. Berndt, L. Harrison, N. Laulainen, N. Larson, and J. Barnard, *Multi-year measurements of aerosol optical depth in the Atmospheric Radiation Measurement and Quantitative Links programs* , Journal of Geophysical Research, **106**, 12099-12107, 2001.

Michalsky, J., Q. Min, J. Barnard, R. Marchand, and P. Pilewskie, Simultaneous spectral albedo measurements near the Atmospheric Radiation Measurement Southern Great Plains (ARM SGP) central facility, J. Geophys. Res., :**108**(D8), 4254, 2003.

Michalsky, J.J., R. Dolce, E.G. Dutton, M. Haeffelin, G. Major, J.A. Schlemmer, D.W. Slater, J.R. Hickey, W.Q. Jeffries, A. Los, D. Mathias, L.J.B. McArthur, R. Philipona, I. Reda, and T. Stoffel, Results from the first ARM diffuse horizontal shortwave irradiance comparison, J. Geophys. Res., **:108**(D3), 4108, 2003.

Michalsky , J., et al., *Broadband shortwave calibration results from the Atmospheric Radiation Measurement Enhanced Shortwave Experiment II* , J. Geophys. Res., :**107**(D16) 2002.

Min, Q.-L., and E. E. Clothiaux, Photon path length distributions inferred from rotating shadowband spectrometer measurements at the Atmospheric Radiation Measurements Program Southern Great Plains site, J. Geophys. Res., **108**(D15), 4465, 2003.

Min, Q.-L., M. Duan, and R. Marchand, Validation of surface retrieved cloud optical properties with in situ measurementsat the Atmospheric Radiation Measurement Program (ARM) South Great Plains site, J. Geophys. Res., **108**(D17), 4547,
2003

Revercomb, H.E., D.D. Turner, D.C. Tobin, R.O. Knuteson, W.F. Feltz, J. Barnard, J. Bosenberg, S. Clough, D. Cook, R. Ferrare, J. Goldsmith, S. Gutman, R. Halthore, B. Lesht, J. Liljegren, H. Linne, J. Michalsky, V. Morris, W. Porch, S. Richardson, B. Schmid, M. Splitt, T. Van Hove, E. Westwater, and D. Whiteman, The Arm Program's Water Vapor Intensive Observation Periods: Overview, Initial Accomplishments, and Future Challenges, Bull. Amer. Meteor. Soc., **84**, 217-236, 2003.

Sengupta .*M*., E. E. Clothiaux, T. P. Ackerman*y*, S. Kato and Q. Min, Importance of Accurate Liquid Water Path for Estimation of Solar Radiation in Warm Boundary Layer Clouds: An Observational Study, *J. Climate,* **16***,* 2997-3010, 2003.